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Modeling channel morphodynamic response to variations in large wood: Implications for stream rehabilitation in degraded watersheds

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ABSTRACT

Anthropogenic modification of forests has often decoupled streams from riparian ecosystems and altered natural wood recruitment processes. Extensive research has shown that large wood significantly impacts channel dynamics, especially in small and intermediate sized forested streams where wood pieces are similar in length to channel width, and many stream rehabilitation efforts now involve the addition of large wood to streams. The primary objective of this research is to investigate the relation between large wood and reach scale channel morphology and hydraulics using a physical model, in order to better inform stream rehabilitation programs and future modeling efforts. Four experiments, each comprising numerous five hour runs, were conducted using a Froude-scaled stream table with wood loads scaled to 0 m^3/m^2, 0.011 m^3/m^2, 0.016 m^3/m^2, and 0.022 m^3/m^2. The addition of large wood significantly decreased the reach-averaged velocity in all experiments, and was associated with decreased sediment transport and increased sediment storage in the reach. Increases in bed and water surface slope compensated for the loss of energy available to transport sediment, and enabled the system to reach a new steady state within the equivalent of 6 to 9 years. Adding wood increased pool frequency, as well as the variability in cross-sectional depth, while causing the reach to undergo a transition from a plane-bed to a riffle-pool morphology. Retention of fine sediment increased the availability of fish spawning substrate, while increased water stage improved connectivity between the channel and the floodplain. The changes in habitat complexity were generally related to the wood load added to the reach, but were also dependent on the orientation and arrangement of the pieces. These results demonstrate that wood may exert a primary control on channel morphodynamics and the availability of aquatic habitat in intermediate sized streams, and suggest that the benefits from stream rehabilitation efforts are highly dependent on project scale. The relatively long time needed to realize habitat benefits demonstrates that long term monitoring of rehabilitation projects is necessary.

1. Introduction

Anthropogenic modification of watersheds has had dramatic impacts on streams throughout the world. Direct wood removal from channels throughout most of the 20th century to facilitate transport, enhance fish passage, and prevent flooding, has dramatically decreased wood loading in many streams (Bisson et al., 1987; Gippel, 1995; Montgomery et al., 2003; Brooks et al., 2004; Lester and Boulton, 2008; Nagamaya and Nakamura, 2010). Decoupling of streams from riparian forests through logging and agricultural or urban land clearing has further decreased in-stream wood loads by altering natural wood recruitment processes (Richmond and Fausch, 1995; Faustini and Jones, 2003; Czarnomski et al., 2008).

Wood depletion through anthropogenic or natural modification of wood recruitment processes has important implications for channel morphodynamics and habitat suitability. Research in small to intermediate sized channels, which represent a large proportion of drainage networks, suggests that wood may exert a significant influence on channel morphology and the availability and quality of aquatic habitat (Montgomery and Buffington, 1997; Montgomery et al., 2003; Buffington et al., 2004; Wohl and Jaeger, 2009; Bocchiola, 2011). By increasing channel roughness, wood decreases the amount of energy available to transport sediment and to erode the bed and banks (Heede, 1972; Gippel, 1995), resulting in increased bed and bank stability. Decreased sediment transport is also associated with increased sediment storage; reductions in the magnitude of the shear stress acting on the bed promote deposition of fine sediment, primarily upstream of channel obstructions (Fetherston et al., 1995; Gippel, 1995; Abbe and Montgomery, 2003; Brooks et al., 2004, 2006; Wilcox and Wohl, 2006). As a result, a large proportion of the sediment storage in forested channels, representing multiple times the annual sediment yield, is directly attributable to wood (Bilby, 1981; Megahan, 1982; Thompson, 1995; Hassan et al., 2005; Andreoli et al., 2007).

Increased storage upstream of log jams, coupled with scour where obstructions force flow concentration, produces a stepped profile in

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which low gradient reaches are punctuated by sudden elevation drops at log steps (Wilcox and Wohl, 2006; Thompson, 2012). The most pronounced morphologic effect of large wood is often an increase in pool frequency; a significant percentage of pools in high gradient streams are associated with wood accumulations (Keller and Tally, 1979; Beechie and Sibley, 1997; Jackson and Sturm, 2002; Faustini and Jones, 2003; Thompson, 2012), and large wood may force a transition from plane-bed to riffle-pool morphologies as bar amplitude and pool frequency increase (Montgomery and Buffington, 1997; Montgomery et al., 2003; Brooks et al., 2004; Buffington et al., 2004). Wood jams also generally increase water stage, thereby promoting floodplain connectivity through avulsion (Collins and Montgomery, 2002; Montgomery et al., 2003; Brummer et al., 2006; Sear et al., 2010; Seo et al., 2010; Wohl, 2011; Phillips, 2012).

Alternating regions of high and low transport capacity are recognized to increase bed surface textural complexity, while the net effect of large wood is generally a decrease in surface grain size (Buffington and Montgomery, 1999; Manga and Kirchner, 2000; Buffington et al., 2004). Field studies involving wood removal suggest that wood loss promotes increased transport from sediment reservoirs, resulting in sedimentation of downstream scour pools (Beschta, 1979; Bilby, 1981; Mosley, 1981; Smith et al., 1993; Gurnell and Sweet, 1998). By increasing sediment transport from upstream storage reservoirs and enhancing sedimentation in downstream scour pools, wood removal reduces bed complexity (Bilby and Ward, 1991; Buffington et al., 2004).

While the importance of in-stream large wood and riparian vegetation have been increasingly acknowledged since the 1970s, most notably in Europe, Australia, and North America, a legacy of earlier land-use practices persists and streams remain depleted of wood in second-growth stands, as well as in urban and agricultural areas (Wilcox and Wohl, 2006; Burnett et al., 2007; Kail et al., 2007; Lester and Boulton, 2008; Nagamaya and Nakamura, 2010). Fish abundance is generally strongly correlated to the availability of pool habitat (Fausch and Northcote, 1992; Sweka and Hartman, 2006), as pools dampen the effects of flow fluctuations by providing protection from high velocities at high flows, as well as refuge from drought at low flows (Hakala and Hartman, 2004; Lester and Boulton, 2008). Sediment stored upstream of large wood structures also provides spawning habitat for salmonids (Bisson et al., 1987; Buffington et al., 2004; Floyd et al., 2009; Nagamaya and Nakamura, 2010). As a result, the addition of large wood has become a common stream habitat-rehabilitation tool in North America, and is increasing in prevalence throughout the world (Bernhardt et al., 2005; Sweka and Hartman, 2006; Kail et al., 2007; Lester and Boulton, 2008; Nagamaya and Nakamura, 2010; Bocchiola, 2011). The most common goals in these stream rehabilitation or enhancement efforts are to increase depth and velocity variability through pool creation, to enhance floodplain connectivity and side-channel development, and to retain the coarse gravels necessary for spawning.

Despite the proliferation of rehabilitation projects involving large wood in recent years, the quantity of wood needed to significantly enhance aquatic habitat remains unknown and modeling attempts largely rely on empirical data (Thompson, 2012). Hypothesis testing through the manipulation of wood loads in the field is restricted by the large temporal and spatial scales at which the relevant processes operate, and by limited monitoring of existing rehabilitation projects (Bernhardt et al., 2005; Kail et al., 2007; Manners et al., 2007; Lester and Boulton, 2008). While physical models provide a means with which to perform controlled experiments, most flume studies to date have focused on wood transport processes and aggregation patterns (e.g. Braudrick et al., 1997; Braudrick and Grant, 2000, 2001; Bocchiola et al., 2006, 2008; Bocchiola, 2011). Several studies have also investigated the morphologic or hydraulic impacts of fixed, often individual, structures (e.g. Cherry and Beschta, 1989; Young, 1991; Wallerstein et al., 2001; Wilcox and Wohl, 2006; Shields and Alonso, 2012). To our knowledge, no research has yet been conducted into the reach scale dynamics associated with assemblages of mobile in-stream large wood interacting with a mobile channel bed. The primary objectives of this paper are therefore two-fold: first, to develop a physical model which examines the morphodynamic effects of interacting pieces of large wood at the reach scale; and second, to evaluate the dependence of these effects on the volume of wood added to the reach. The goal, in effect, is to test the hypothesis that the influence of large wood on aquatic habitat is a function of the amount of wood added, and therefore the scale of the rehabilitation program needed.

2. Methods

2.1. Experimental design

A reach scale physical model was constructed based on the planform of Fishtrap Creek, an intermediate sized tributary to the North Thompson river in the interior plateau of British Columbia, which drains a watershed area of 158 km^2. The Fishtrap Creek study reach, established in 2004 following a high intensity forest fire that burned 68% of the watershed, is described in detail by Andrews (2010) and Eaton et al. (2010). The physical model represents an approximate 1:30 Froude-scale model of the prototype (see Table 1). The channel has non-erodible banks constructed from Styrofoam, and a mobile bed comprising a layer of sediment 0.08 m thick, which represents a sediment reservoir of approximately four to five times the mean flow depth. This bed material is composed of a sand mixture scaled to the median grain size of the bed material surveyed in Fishtrap Creek. To maintain Froude similarity, discharge and time were scaled according to the following equations:

$$T_r = L_r^{0.5} \tag{1}$$

$$Q_r = L_r^{2.5} \tag{2}$$

where T_r is the relative time and Q_r the relative discharge.

Four experiments were conducted with varying wood loads in order to evaluate the morphodynamic effects of different quantities of wood. The wood load for each experiment is simply the total volume of wood added to the reach, divided by the total bed area. The wood loads added in experiments 1 to 3 were selected to represent a range of wood loads typically found in natural streams, and therefore a range of potential rehabilitation targets. The highest wood load, added in experiment 3, is roughly equivalent to the current loading in Fishtrap Creek, while the moderate wood load added in experiment 2 approximates the pre-fire wood load in the stream.

The wood pieces used in the experiments were scaled geometrically based on piece lengths and frequencies measured in wood surveys performed in the prototype study reach in 2008–2009 (Andrews, 2010). Cylindrical pine dowels used in a series of pilot studies exhibited behavior that fundamentally differed from the wood dynamics observed in the prototype. To improve the realism of the model, denser maple pieces with square cross sections were used instead. Root wads and branch snags were also attached to many of the pieces to promote interactions between the pieces and increase piece stability. Piece diameter was consistent for all wood pieces, and was scaled to the mean piece diameter in the prototype system (equivalent to approximately two thirds of the mean flow depth). Three different piece lengths were

Table 1
Parameter lengths for the prototype and model systems are compared.

Parameter	Prototype	Model
Width	10–12 m	0.34 m
D_{50}	35 mm	1.4 mm
Peak discharge	7.5 m^3/s	1.6 L/s
Time	27 hours	5 hours

used in the experiments, corresponding to the three major size classes surveyed in the prototype. The 0.4 m pieces, representing the second largest size class (8–16 m) measured in Fishtrap Creek, had a ratio of length to bankfull width of >1, and were therefore large enough to span the channel width, often acting as key members for jam initiation. The largest size class (16–32 m), which contributed only 2% of the large wood surveyed, was not included in the experiments as it was expected that such large wood (with a ratio of length to bankfull width of >1.5) would remain suspended across the channel for the duration of the experiments regardless of the angle of entry. It was therefore assumed that these pieces would serve the same purpose as the suspended 0.4 m pieces, enabling the addition of the 2 % contribution by these pieces to the 0.4 m size class. Shorter 0.1 m and 0.2 m pieces were designed to represent segments of full trees.

The experimental treatments are summarized in Table 2. Each experiment was comprised of a sequence of five hour runs with a discharge equivalent to the mean annual maximum daily flow (Q_p = 1.6 L/s in the model or 7.5 m^3/s in the prototype system). Assuming that only these maximum annual flows are sufficient to mobilize the bed material, each run was equivalent to a year of effective flow. While this clearly represents a simplification, it is generally reasonable to assume a bankfull threshold for sediment transport in the coarse-grained, mountain streams used by many salmonids (Buffington et al., 2004). Furthermore, significant wood and sediment transport were not observed in the model reach or the prototype stream at discharges below the mean annual maximum daily flow.

Throughout the runs sediment was added at the stream inflow at a rate of 55–60 g/min using a rotating feeder. At steady state, this produced a (scaled) bedload transport rate of approximately 190 m^3/year, which is consistent with the typical bed material transport rates estimated for Fishtrap Creek (Eaton et al., 2010). Runs were first conducted without wood to establish a steady state sediment transport rate and channel morphology. In experiment 0 a pulse of sediment was then released from the upstream end of the reach to simulate a jam failure, while in experiments 1 to 3 wood was added to the reach at low flow (0.4 L/s). The experimental reach at steady state in experiments 1 to 3 is shown in Fig. 1.

Wood addition was designed to mimic “soft engineering” techniques, as wood was added to the reach at randomly selected cross sections and angles and left un-fixed (Kail et al., 2007). While this episodic input model is not representative of continuous natural wood input processes, it represents the simplest first step in modeling the morphodynamics associated with multiple pieces of mobile wood, and is representative of the pulsed inputs of wood associated with stream rehabilitation projects and natural disturbance events. Following the attainment of a new steady state, wood was removed from the reach in experiments 1 to 3.

2.2. Data collection and analysis

Throughout the experimental runs sediment output was collected in a 0.177 mm mesh bag located at the stream table outlet and removed at 15 minute intervals. The output samples were then oven-dried at 250 °C, and weighed to determine the average sediment output per unit time. Sediment storage was determined at each 15-minute interval by calculating the difference between the cumulative input and output values. Volumes were derived from dried weights using a specific dry sediment weight of 2650 kg/m^3 (Eaton and Lapointe, 2001). Cumulative sediment storage was used to assess whether a steady state transport condition had been attained; wood was only added to or removed from the model once steady state had been reached. As the model represents a closed system with multiple measurements of sediment input rate performed each run and all sediment output measured, the estimated error in storage was <1%.

Conductivity data were also collected throughout the experiments using a tipping bucket with a saline drip at the upstream end coupled with a conductivity meter at the outlet. By comparing back-calculated depth with measured depth, which is calculated based on the time integral of the area beneath the conductivity pulse, Zimmermann (2009) found that the harmonic mean velocity was the most accurate measure of reach-average velocity. Given that such calculations were not performed during this research, the peak velocity was primarily used in comparisons between different wood loads since estimates of the peak were associated with the lowest uncertainty, while harmonic mean velocity was used to calculate flow depth.

Velocity measurements were obtained from the temporal profile of the conductivity data by calculating the travel time of the saline pulse from the injection site to the conductivity meter. The velocity associated with the peak (v_p) of the saline pulse is simply:

$$v_p = \frac{x}{t_p} \tag{3}$$

where x is the travel distance between the tipping bucket and the conductivity probe and t_p is the time between the slug injection and the peak concentration associated with the pulse. Variability in flow velocity was then determined by calculating the width of the velocity pulse at a value of 1/8 of the peak conductivity for a subsample of the conductivity data from each steady state run.

Determining the harmonic mean velocity required the calculation of the probability density function, $px(t)$, and the time integral of concentration, Ix, at the fixed point x, which required that a pulse be defined. Pulses were isolated using a threshold conductivity defined as a conductivity at least 6σ above the background rate. Harmonic mean velocity was then calculated using:

$$px(t) = \frac{c(x,t)}{Ix} \tag{4}$$

$$Ix = \int c(x,t) \cdot dt \tag{5}$$

where x is the location of the downstream conductivity probe and t is the time since the injection (Waldon, 2004). Harmonic mean velocity (v_{hm}) was then calculated as:

$$v_{hm} = \frac{x}{\frac{1}{\int \frac{1}{t}(px(t) \cdot dt)}} \tag{6}$$

Water surface elevation was recorded following each experimental run by measuring the distance from the bank top to the water surface at 0.25 m intervals. The stage measurements were made to the nearest 0.5 mm, with an estimated error of 0.5 mm. The recorded values were subtracted from the bank height elevation at each measurement point to determine the water surface elevation above an arbitrary datum. Reach-averaged mean gradient, S, was determined according to:

$$S = \frac{\delta E}{L} \tag{7}$$

where E is the water surface elevation in meters, and L the distance over which water surface elevation was measured.

Table 2
Treatments employed in experiments 0 to 3 are described.

Exp.	Treatment	Model $[m^3/m^2] \times 10^2$	Prototype $[m^3/m^2] \times 10^2$
0	Sediment pulse	–	–
1	Low wood load	0.037	1.1
2	Mod. wood load	0.053	1.6
3	High wood load	0.073	2.2

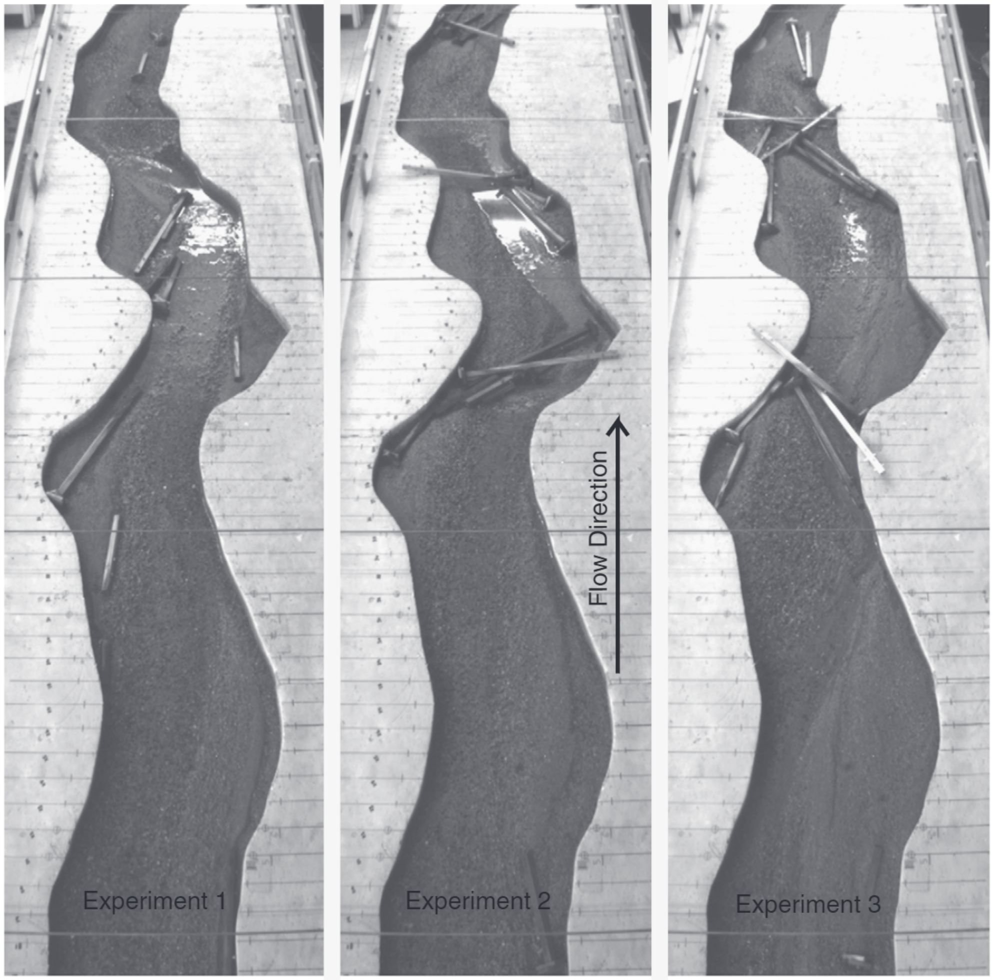

Fig. 1. The experimental reach at steady state (immediately prior to wood removal) is shown for experiments 1 to 3. Flow direction is toward the top of the page (black arrow).

Changes in channel morphology were assessed using longitudinal profiles along the mean cross-sectional bed elevation and the channel thalweg – or minimum cross-sectional bed elevation – constructed from laser images captured at 0.05 m intervals. Residual depths were calculated from the profiles of the channel thalweg using the method described by Lisle (1987) and pools were defined as locations where the difference in elevation between the minimum point of the topographic depression and the maximum height of the successive riffle was greater than 25% of the calculated bankfull depth, according to the definition of Montgomery et al. (1995). Pool lengths were then measured as the horizontal distance between adjacent riffles, with the measurement error estimated as the distance between cross sections (0.05 m). This produced an error of approximately 2% in the estimates of the percentage of the total reach length occupied by pools. Overhead photographs were used to determine the length of pools located near the first or last surveyed cross section, to assure that separate pools were not grouped together, and to assess the widths of the smallest pools. Pools were then defined as log-affected or non-log-affected according to the methods of Webb and Erskine (2003).

Finally, facies boundaries were mapped based on visual inspection at the end of each run on a base map of the channel banks. Photos were then taken of a 0.15 by 0.2 m segment of each facies. To determine grain size, Wolman-type analyses were conducted on 20 of the facies photographs by measuring grain sizes in Adobe Illustrator at the vertices of an imposed grid (Wolman, 1954). Each measured facies was classified according to five grain size categories, ranging from very fine to very coarse. The remaining facies images were then classified visually by referencing the photographs of the measured facies, with a 10% mis-identification rate. Appropriate spawning substrates were defined according to the work of Buffington et al. (2004) as very fine to medium facies (D_{50} < 1.0 mm), with an associated identification error of 10%.

Five wood metrics were used in the analyses to assess the effects of wood addition on channel morphodynamics. Wood load and piece frequency were simply defined as the volume or number of pieces of wood added per unit of channel bed, and were assigned prior to wood addition in each experiment. Jam frequency, mean blockage ratio, and the total dimensionless projected area were calculated at steady state for each experiment following wood addition. Jams were defined as accumulations of at least three pieces, with at least two points of contact. Blockage ratio was calculated according to the methods of Gippel et al. (1992) and Webb and Erskine (2003). The projected area (A_{pi}) of each wood piece was first calculated:

$$A_{pi} = L \cdot D \cdot sin(\sigma) \cdot P \tag{8}$$

where L and D are the piece length and diameter in meters, σ is the piece angle relative to the flow direction, and P is the proportion of wood submerged by the flow. Flow area (A_f) was then calculated using:

$$A_f = \frac{Q}{v_{hm}} \tag{9}$$

where Q is the discharge and v_{hm} is the harmonic mean flow velocity. A blockage ratio (B_{pi}) was finally calculated for each piece according to:

$$B_{pi} = \frac{A_{pi}}{A_f} \tag{10}$$

The blockage ratio was then aggregated throughout the reach to provide a useful metric of reach scale hydraulic impact for each experiment, which combined the effects of wood load and piece orientation. The total projected area (A_p) of the wood pieces for each experiment, was calculated using:

$$A_p = \sum A_{pi} \tag{11}$$

To standardize these results the projected area was then non-dimensionalized by dividing by the bed area:

$$A_p' = \frac{A_p}{L \cdot W_b} \tag{12}$$

where L is the length of the reach, and W_b is the bankfull width of the reach in meters. The proportion of each piece of wood that was submerged (P) was estimated visually at the end of each run to the nearest 5%, with an approximate measurement error of 5%. As a result, estimates of blockage ratio and total projected area also contained a 5% measurement error.

3. Results

3.1. Experiment 0

The first experiment was used to establish a steady state morphology in the reach without large wood, and to test the effects of releasing a sediment pulse at the upstream end. Bar formation began immediately in protected bends at 0.4 m, 2 m, and 2.4 m once the flow was increased to Q_p. Steady state sediment transport was achieved rapidly following a brief period of aggradation in the first two hours of the experiment (Fig. 2C). Despite the observed bar formation during the aggradational period, the longitudinal mean bed profile at steady state appears featureless (Fig. 2A).

The longitudinal profile of the minimum bed elevation – the channel thalweg – meanwhile shows significant pool development, especially in the middle to lower segment of the reach; pool spacing was 2.6 times the channel width, with large pools at 1.9 m, 2.5 m, and 4.5 m, and smaller pools located at 1.2 and 3.6 m (Fig. 2B). In general pool and bar locations were dictated by the channel planform, with long pools located at the inside of bends, and bars located in the protected hollows. Pool and bar development was largely absent in the straighter upper segment of the reach, which retained a plane-bed morphology throughout the experiment.

After 10 hours of flow, a 3100 cm^3 pulse of sediment (equivalent to approximately half the annual bed material load) was released from the upstream end of the reach, causing a brief 3-fold increase in sediment transport approximately 45 minutes later (Fig. 2D). Steady state sediment transport conditions were re-established within 2 hours of the pulse release, with the profile of the mean bed elevation revealing only slight aggradation in the upper 2 m of the reach, and no change downstream. While pool spacing also remained constant, the profile of the minimum bed elevation shows that the location of the largest pool shifted 0.5 m downstream to 2.4 m. Pool size also changed as the mean pool length and depth each decreased by 16%, and the percentage of the total reach length occupied by pools decreased from 50 to 42%. Reach-average mean bed and water surface gradients did not change.

The sediment pulse release also produced sedimentological changes in the reach. While facies number remained constant, with 16 facies in the reach both before and after the pulse release, textural changes in the surface material occurred. Median grain size increased by 10% due to a 9% increase in the very coarse facies ($D_{50} > 1.4$ mm)

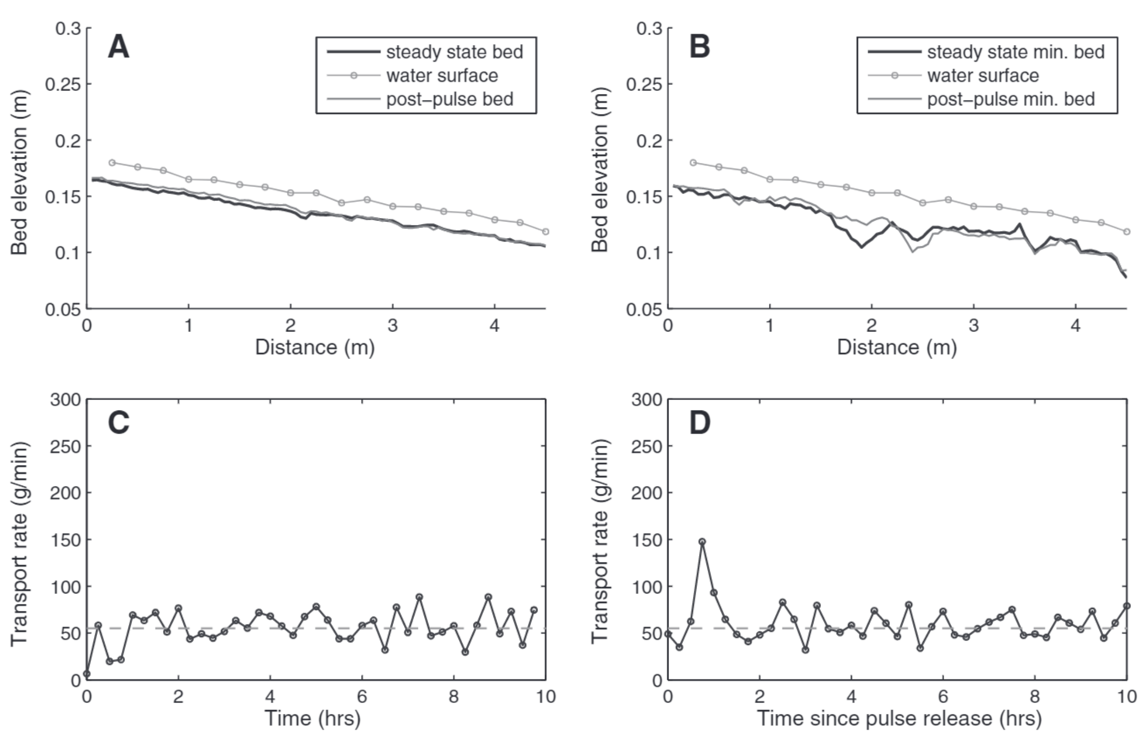

Fig. 2. (A) Longitudinal profiles of the mean bed elevation at steady state prior to and after the sediment pulse release in experiment 0, as well as the water surface profile following the pulse release. (B) Longitudinal profiles of the minimum bed elevation (thalweg) prior to and following the sediment pulse release, as well as the water surface profile. (C) Sediment transport rates over the time period prior to the pulse release, with the sediment input rate represented by the dashed line. (D) Sediment transport rates following the pulse release, with sediment input rate represented by a dashed line.

and a 21% increase in the medium facies (D_{50} = 0.7–1.0 mm), which appeared to largely replace the coarse facies (D_{50} = 1.0–1.4 mm). The two finest facies (D_{50} < 0.7 mm, equivalent to D_{50} < 21 mm in the prototype) decreased by 11% following the pulse release.

3.2. Experiment 1

The profile of the mean bed elevation at steady state (Fig. 3A) prior to wood addition is again generally featureless, while the profile of minimum bed elevation (Fig. 3B) shows a plane bed morphology in the upper 3 m of the reach, with pool formation occurring in the lower 1.5 m. Following the attainment of steady state transport after 10 hours, the lowest wood load was added to the reach at low flow (0.25*Q_p or 0.4 L/s). Once the flow was increased to Q_p, a small amount of re-organization of wood in the first 15 minutes caused a slight increase in sediment transport, and an associated decrease in net sediment storage (Fig. 3C).

Wood addition was associated with an immediate 13% decrease in flow velocity, which then remained constant until wood was removed. The morphologic and sedimentological adjustments associated with wood addition, however, occurred gradually throughout the course of the experiment. Flow deflection by four obliquely-oriented pieces at 2.5–3 m, for example, allowed the expansion of a fine bar that had originally formed in a protected bend, while causing a scour hole to form downstream at the opposite bank. The scoured material then produced a coarse bar which also expanded over time, causing further deflection of the thalweg and increasing the proportion of the bed occupied by the coarsest facies (D_{50} > 1.4 mm) by 35%. Despite significant re-organization of wood throughout the experiment, no jams formed and the pieces remained randomly distributed (Fig. 1).

As sediment transport increased over time, net sediment storage slowed (Fig. 3C), becoming negligible between 27 and 30 hours after wood addition. The longitudinal profile of mean bed elevation at this new steady state condition (Fig. 3A) shows that the aggradation of 2000 cm^3 of sediment did not significantly affect the mean bed morphology, with degradation near the outlet balanced by minor aggradation in the upper reach, and little change in reach-average bed or water surface gradient.

Changes in bed morphology are more apparent from the minimum bed profiles shown in Fig. 3(B). Scour produced a log-induced pool at 0.3 m, decreasing pool spacing in the reach from 2.6 to 2.2 channel widths and increasing the length of the reach occupied by pools by nearly 20%. Pools located at 3.2 and 3.6 m deepened and shifted slightly upstream, as a result of the flow deflection caused by the oblique pieces described above. At steady state, 33% of the pools in the reach were defined as log-affected. Although the average pool length remained constant following wood addition, the mean pool depth increased marginally.

To restore steady state sediment transport, the mean bed gradient was expected to increase following wood addition. The bed gradient decreased by 6%, however, while the thalweg profile became increasingly stepped (Fig. 3B) due to the increased variability in transport capacity which produced alternating sites of sediment transport and deposition. The increased heterogeneity of the bed morphology and transport capacity was accompanied by greater variability in surface texture; at steady state the number of texturally distinct facies had increased by 70%, while the median surface grain size actually increased by 20% largely due to the expansion of the coarse bar described above. The proportion of the bed occupied by substrates appropriate for spawning (D_{50} < 1.0 mm) decreased dramatically.

Wood removal caused an immediate change in channel morphodynamics. Flow velocity increased by 6%, recovering only half way to the pre-addition value. Qualitative observations suggest that the upper segment of the reach rapidly reverted to a plane bed morphology as fine bars were eroded and pools were partially in-filled by sediment. While pool frequency remained constant following wood removal, the average pool length decreased by nearly 40%. As a result, the length of the reach occupied by pools following wood removal was substantially lower than in

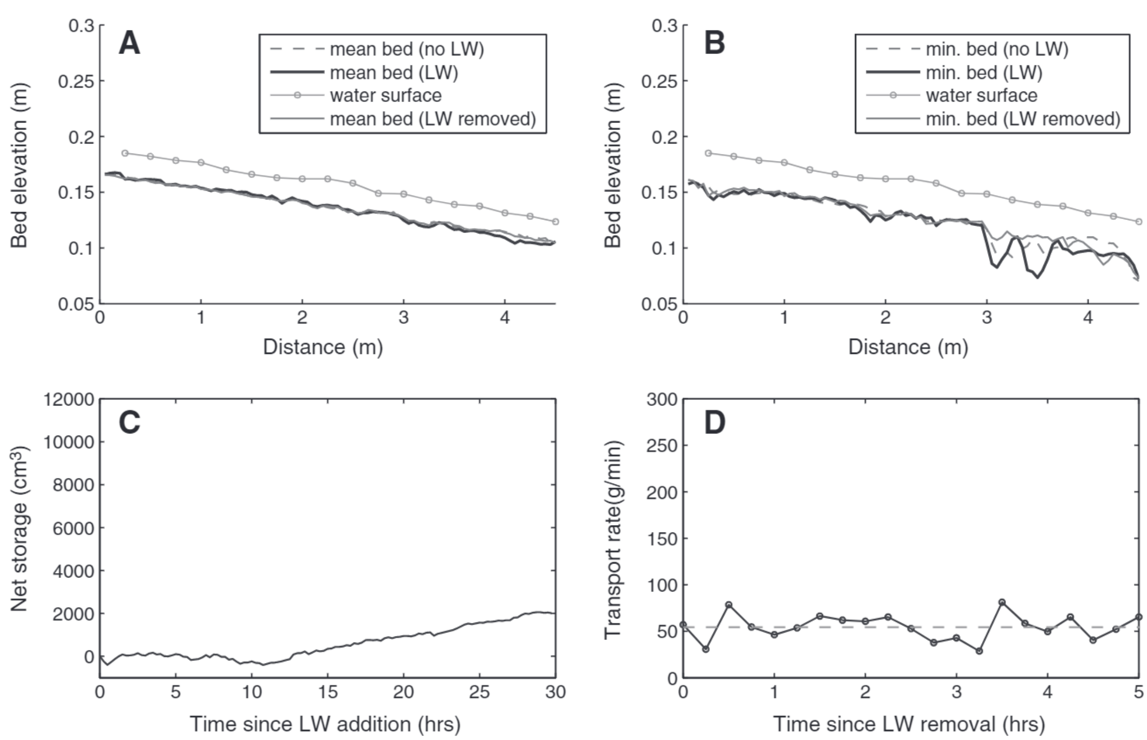

Fig. 3. (A) Longitudinal profiles of the mean bed elevation at steady state prior to and after the addition of the lowest wood load in experiment 1, as well as following wood removal are shown along with the water surface profile with wood in the reach. (B) Longitudinal profiles of the minimum bed elevation (thalweg) prior to and following wood addition, as well as after wood removal. (C) Sediment storage during the period of aggradation following wood addition. (D) Sediment transport rates following wood removal, with sediment input rate represented by a dashed line.

the original pre-wood morphology, despite the sustained increase in pool frequency. Similarly, pool in-filling reduced the average pool depth by over 50%.

The effects of wood removal on sediment transport were comparatively minor; while a small pulse passed through the outlet 30 minutes after wood removal, it was within the typical range of variability in sediment transport (Fig. 3D). The nominal response to wood removal likely reflects the lack of significant sediment storage in the reach, as little sediment evacuation was necessary to restore the pre-wood bed morphology. Further, in the absence of jams, sediment was likely stored in small wedges associated with individual wood pieces and the little evacuation that did occur was therefore distributed over time rather than condensed into a sediment pulse.

3.3. Experiment 2

The bed morphology at steady state, achieved after 13 hours, strongly resembles the morphology observed in the previous experiments (Fig. 4A and B). However, while the longitudinal mean and thalweg profiles appear similar to the previous two experiments, with an apparently featureless plane-bed morphology in the upper reach and pool formation in the lower 1.5 m, the reach actually contained nearly twice as many pools. A comparison of pool size reveals that although pool length was similar in all three experiments, the mean pool depth and median depth were 20% and 50–70% lower than in the previous experiments, respectively. This suggests that many of the pools were deep enough to surpass the threshold depth for pool definition, but were not large enough to qualitatively alter the channel profile.

The addition of large wood caused an immediate 11% decrease in flow velocity, which was similar in magnitude to the relative decrease in velocity experienced in experiment 1. The morphologic changes, however, were again more gradual, and followed the re-organization of the wood in the reach. Following wood addition there was a period of significant wood movement, which produced a brief decrease in net sediment storage (Fig. 4C). Several wood pieces formed a jam nearly immediately at 2.2 m, which then amassed additional pieces, reaching a total of 9 pieces by the end of the five-hour run. Two smaller jams also formed at 3.1 and 4.5 m where they remained for the entirety of the experiment. The period of jam-building was associated with rapid aggradation, which was then followed by several hours of quasi-steady-state sediment transport as scour beneath the jam allowed flow to pass through and minimized aggradation (Fig. 4C). Qualitative observations suggest that the re-orientation of two of the jam members to a perpendicular position around hour 7 dramatically increased the blockage ratio and decreased the porosity of the jam, enabling aggradation to occur for approximately 17 hours. The wood distribution at steady state, immediately prior to wood removal, is shown in Fig. 1. While the piece number was too small to enable statistical analysis of the distribution, it appears that jams primarily formed around those 0.4 pieces which had one end suspended on the channel bank. These key pieces subsequently trapped smaller, more mobile pieces, producing an aggregated wood distribution.

The gradual accumulation of over 5500 cm^3 of sediment is reflected in the mean bed profile (Fig. 4A), which reveals significant aggradation in the 2.2 m segment upstream of the largest jam. In general, jams forced the expansion of fine bars upstream. Scour at the jam location, in turn, dictated pool location while promoting deposition of scoured material in coarse downstream bars. These changes are reflected in the thalweg profile (Fig. 4B) which shows that the formation of the jam near 2.2 m caused an upstream shift in the location of the two largest pools, by creating scour beneath the jam. The previous pools at 3.2 and 3.6 m, meanwhile, were infilled by deposition of a coarse bar downstream of the jam at 3.1 m, and aggradation of a fine bar upstream of the jam at 4.2 m.

At steady state, which was achieved approximately 25 hours after wood addition, channel gradient and reach morphology had significantly changed. Unlike experiment 1, the reach-average bed gradient actually increased by 10%, suggesting an increase in the potential energy of the system was required to re-attain steady state sediment transport. The relatively small change in pool frequency and size (compared with

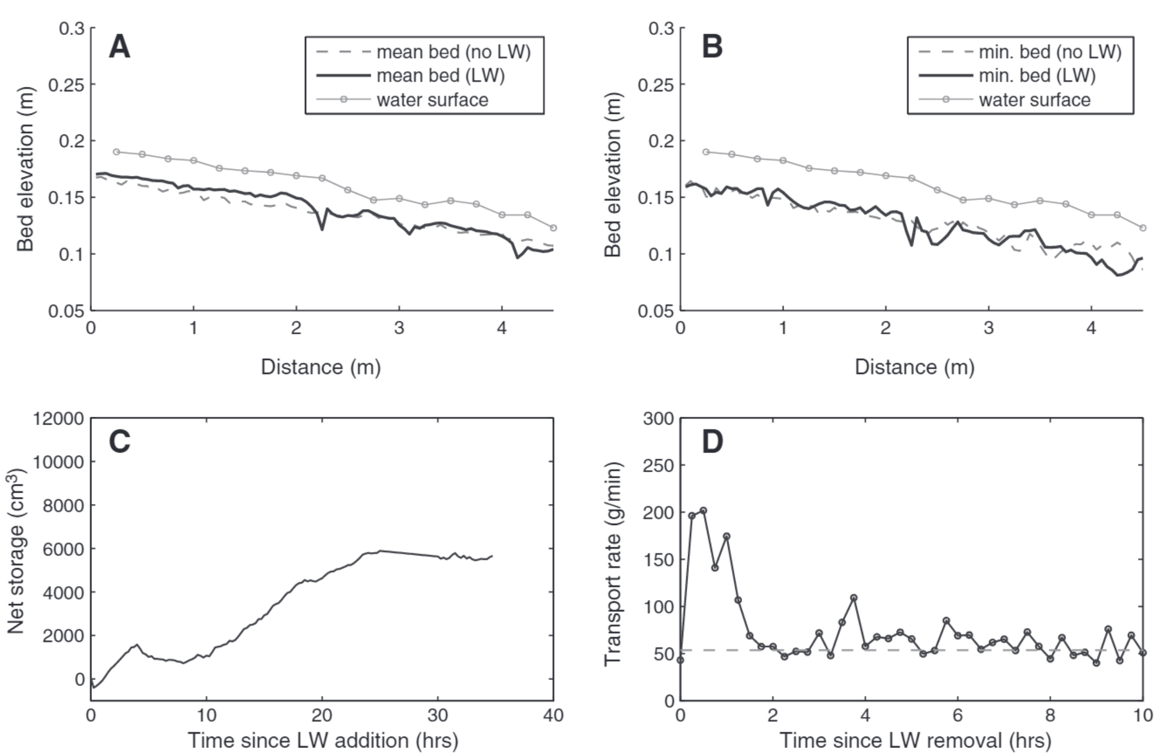

Fig. 4. (A) Longitudinal profiles of the mean bed elevation at steady state prior to and after the addition of the moderate wood load in experiment 2, as well as the water surface profile with wood in the reach. (B) Longitudinal profiles of the minimum bed elevation (thalweg) prior to and following wood addition. (C) Sediment storage during the period of aggradation following wood addition. (D) Sediment transport rates following wood removal, with sediment input rate represented by a dashed line.

the previous experiment) likely reflects the already high pool abundance and small pool size prior to wood addition in the current experiment; while the number of pools only increased by 20%, there were nearly twice as many pools at steady state than in the previous experiment. Facies number nearly doubled; while there was once again an increase in the very coarse facies due to deposition of scoured material downstream of jams, it was counteracted by an increase in fine and medium facies in the bars which formed upstream of jams, resulting in a 5% decrease in median grain size.

Wood removal after 35 hours caused dramatic morphodynamic changes in the reach. Qualitative observations suggest that coarse bars were already being covered by fine sediment eroded from fine bars at a discharge equivalent to half of the peak flow (0.8 L/s). Changes were even more dramatic once the peak discharge was imposed; sediment transport increased 4-fold within the 30 minutes following wood removal and remained high for nearly 90 minutes as sediment pulses associated with wood jams and individual pieces were rapidly evacuated from the system (Fig. 4D).

3.4. Experiment 3

The final experiment involved the addition of the highest wood load. As with previous experiments, runs were conducted until a steady state transport rate was reached prior to wood addition. At steady state the profile of the mean bed elevation was again featureless (Fig. 5A), while the thalweg profile showed pool development in the lower 1.5 m, with a plane bed morphology upstream (Fig. 5B). While the number of pools at steady state prior to wood addition was relatively low, the mean pool length and depth were nearly double that of the earlier experiments, suggesting that it was the smaller pools which were absent from the reach. The length of the reach occupied by pools was similar to that of experiments 0 and 1.

As in the previous experiments, wood addition was accompanied by an immediate decrease in flow velocity – in this case by 15% – as well as rapid changes in wood organization. Following the addition of large wood there was again significant wood movement in the first 15 minutes, causing a brief decrease in the net storage of sediment in the reach (Fig. 5C). During this time, two jams formed at 3 and 3.4 m, inducing a prolonged period of aggradation, which persisted for nearly 40 hours (Fig. 5C). The movement of a large piece approximately 15 hours after wood addition formed a jam at 2.3 m, while the jam located at 3 m moved downstream to join the larger jam at 3.4 m between 20 and 25 hours after wood addition. Transient decreases in sediment storage occurred as a result of sporadic wood movement during this period.

As in previous experiments, gradual morphologic adjustments occurred throughout the experiment. The two jams which formed in the reach, located at 2.2 and 3.3 m (Fig. 1), created deep scour pools, while promoting aggradation upstream. Jam formation again appears to have produced a non-random, aggregated distribution. Qualitative observations show that the bar which formed upstream of the largest jam at 3.3 m became emergent half way through the run and nearly forced a channel avulsion. In the upper segment of the reach, a single oblique piece produced scour along the left bank by deflecting flow, thereby allowing a fine bar to expand along the opposite bank and transforming the plane bed to a riffle-pool morphology. In general the flow deflection by individual wood pieces and jams, as well as bar expansion, again increased the sinuosity of the thalweg.

The changes in channel morphology at steady state were similar to the previous experiment, though generally greater in magnitude. The significant accumulation of sediment was reflected primarily in the upper segment of the reach (Fig. 5A), causing the reach-average bed gradient to increase by over 15%. There was also a marked increase in the bed variability as pool frequency more than tripled, though the number of pools remained slightly below the pool number in the previous experiment. Similarly, while the length of the reach occupied by pools increased by nearly 70%, it remained below the value recorded for experiment 2. The increased variability in flow regime was also reflected in the surface sedimentology; the number of facies in the reach increased by 60%, while the median grain size decreased by 10%,

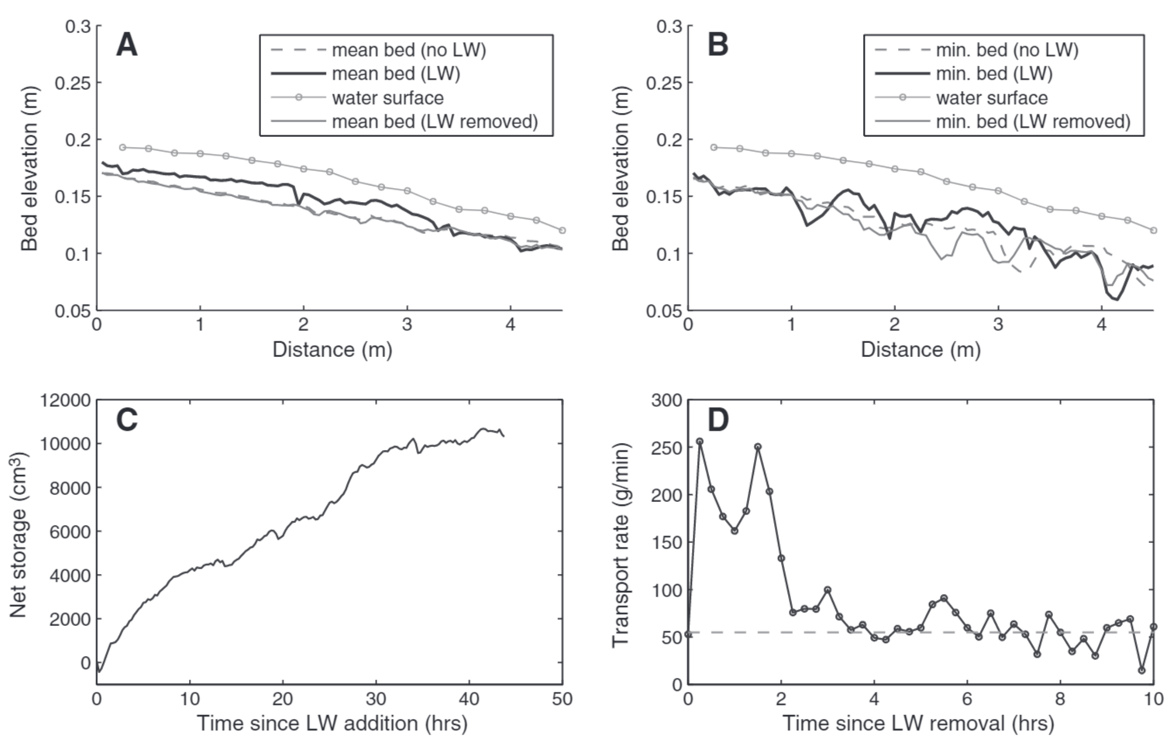

Fig. 5. (A) Longitudinal profiles of the mean bed elevation at steady state prior to and after the addition of the highest wood load in experiment 3, as well as following wood removal are shown along with the water surface profile with wood in the reach. (B) Longitudinal profiles of the minimum bed elevation (thalweg) prior to and following wood addition, as well as after wood removal. (C) Sediment storage during the period of aggradation following wood addition. (D) Sediment transport rates following wood removal, with sediment input rate represented by a dashed line.

driven by increases in the fine and very fine bars associated with aggradational zones, which provide optimal spawning habitat.

Wood removal caused a 5-fold increase in sediment transport, as two distinct sediment pulses were evacuated from the reach in the first 2 hours (Fig. 5D). Unlike in experiment 1, the dramatic increases in sediment transport resulting from the erosion of wood-formed bars was sufficient to completely in-fill half of the pools, 70% of which had been considered log-affected. These morphologic changes were associated with dramatic increases in both measures of the median channel slope, and erosion of the previously aggraded upper segment of the reach allowed a full recovery of the reach-average bed gradient. Qualitatively, the mean bed profile following wood removal appears nearly identical to the pre-addition profile (Fig. 5A).

3.5. Aggregate results

The aggregate results from the four experiments can be used to address the second objective of the analysis: to quantify the effects of wood load and orientation on channel morphodynamics. While wood load and piece frequency are the most commonly used metrics for quantifying wood in a reach, the average blockage ratio of the wood pieces, the total projected area of the wood, and the jam frequency were also considered in the analysis. The values for each of these metrics are summarized in Table 3. The reach scale morphologic and hydraulic adjustments associated with wood addition are presented in Tables 4 and 5. Due to the small number of experiments, statistical analysis of the relations was not possible; the explanatory strength of the metrics have instead been qualitatively assessed.

The addition of large wood significantly reduced the reach-averaged velocity, even following the addition of the lowest wood load in experiment 1, but did not systematically change the variability in velocity measurements or the width of the conductivity pulses (Fig. 6). The effects of wood addition were generally immediate, and flow velocities did not change during the period following the initial wood input. The mean velocity at steady state with large wood in the channel appears to correlate with wood load, piece frequency, the mean piece blockage ratio, and the dimensionless projected area of the added wood.

Decreases in mean flow velocity associated with enhanced roughness and flow resistance are reflected in sediment transport rates, which decreased following wood addition. The total volume of storage that accumulated in the reach following wood addition varied between the experiments (Table 4), and appears to correlate with the wood load, piece frequency, and projected area of the wood. The ratio of storage to wood volume ranged from 3.3 to 8.0, while the actual volume of sediment stored per piece of wood ranged from 120 to 300 cm^3, equivalent to sediment storage of 3.3 to 8.2 m^3 per wood piece in the prototype system. The storage efficiency again appears to be positively related to wood load, piece frequency, and the projected area of the wood.

Enhanced spatial variability in flow competence created heterogeneously distributed sediment storage, and greater facies diversity. The change in facies number following wood addition is not related to any of the wood metrics considered in this analysis. Facies number prior to wood or pulse addition is fairly consistent, and appears to increase by a similar margin regardless of the quantity of wood added, or its subsequent orientation and arrangement (Fig. 7A). Increased sediment storage in the reach enabled the retention of the medium facies and finer (D_{50}<1 mm, equivalent to D_{50}<30 mm), which increased in experiments 2 and 3 by 19.6% and 20.2%, respectively. This fining, with coarse facies covered by the finer retained sediment, resulted in decreases in the median grain size of 5% and 10% respectively, but is not obviously related to any of the wood-related metrics considered in the analysis. Conversely, following the addition of the lowest wood load in experiment 1 there was a marked coarsening of the bed surface as the very coarse facies (D_{50} increased by 35%). The percentage of the surface area with D_{50}<1.0 mm at steady state, which was deemed suitable for spawning habitat, appears to be related to all wood metrics considered in the analysis, and most strongly to the total projected area of the wood (Fig. 7B).

Uneven distribution of sediment storage dramatically altered the channel profile and planform. Profiles of minimum bed (thalweg) elevation reveal an increasingly stepped profile following wood addition. In general, the originally plane-bed upper segment of the reach transitioned to a riffle-pool morphology. As expected, the addition of wood was associated with increased variability in cross-sectional depths. The number of pools at steady state, as well as pool spacing (measured in multiples of the bankfull channel width), are positively related to all of the wood-related metrics used in the analysis, and especially to the mean blockage ratio (Fig. 8A) and total dimensionless projected area of the wood. The percentage of the reach occupied by pools at steady state, though positively related to all of the wood metrics, appears to correlate most closely to the jam frequency in the reach (Fig. 8B).

Pool depth and length were also measured for each pool. Mean pool length and depth were 0.36 m and 0.014 m, respectively, for the aggregated results of all four experiments at steady state, which is equivalent to a length and depth of 11 m and 0.42 m in the prototype system. The average pool length and depth did not differ significantly (α=0.05) between the four experiments at steady state, indicating that the volume of wood added does not dictate pool dimensions. The mechanism for pool formation, however, does appear to exert a significant influence on pool length, as non-log-affected pools were significantly longer (0.39 m or 12 m) than the log-affected pools (0.27 m or 8.1 m), which formed due to log-related scour (Fig. 9A). The difference in the depth of log-affected (0.012 m or 0.36 m) and non-log-affected (0.014 m or 0.43 m) pools is not significant (Fig. 9B). Non-log-affected pools were generally observed along the outside of channel bends, while

Table 3
The values of each wood metric used in the comparisons of morphodynamic impacts of wood addition are summarized.

Exp.	WL	P_f	J_f	BR_{avg}	PA_{total}
	[m^3/m^2]×10^2	[pieces/m^2]	[jams/m]	–	–
1	0.037	9.7	0	0.12	0.010
2	0.053	13.6	0.67	0.23	0.029
3	0.073	19.4	0.44	0.21	0.035

WL = wood load, P_f = piece frequency, J_f = jam frequency, BR_{avg} = mean piece blockage ratio, PA_{total} = dimensionless total projected area of all wood pieces.

Table 4
A summary of the steady state morphology of the reach in each experiment.

Exp.	T_R	v	ΔSS	SS_e	N_{facies}	A_{sp}
	[min]	[m/s]	[cm^3]	[m^3/m^3]	–	[% area]
0	–	0.35	0	0	15	29
1	1800	0.32	1850	3.3	27	34
2	1860	0.31	4890	6.1	26	59
3	2640	0.30	9110	8.0	26	64

T_R = recovery time, v = reach-average velocity, ΔSS = sediment storage volume, SS_e = sediment storage efficiency, N_{facies} = number of distinct facies, A_{sp} = spawning area.

Table 5
A summary of the steady state reach morphology and hydraulic condition for each experiment.

Exp.	VAR_{Depth}	SP_{pool}	L_{pool}	ΔH	S
	[m]	[W_b]	[% length]	[mm]	[m/m]
0	0.037	2.6	42	0	0.014
1	0.052	2.2	50	2.1	0.015
2	0.053	1.2	80	6.1	0.016
3	0.099	1.3	69	8.3	0.017

VAR_{Depth} = variability of the channel depth, SP_{pool} = pool spacing, L_{pool} = pool length, ΔH = stage change, S = reach-average water surface gradient.

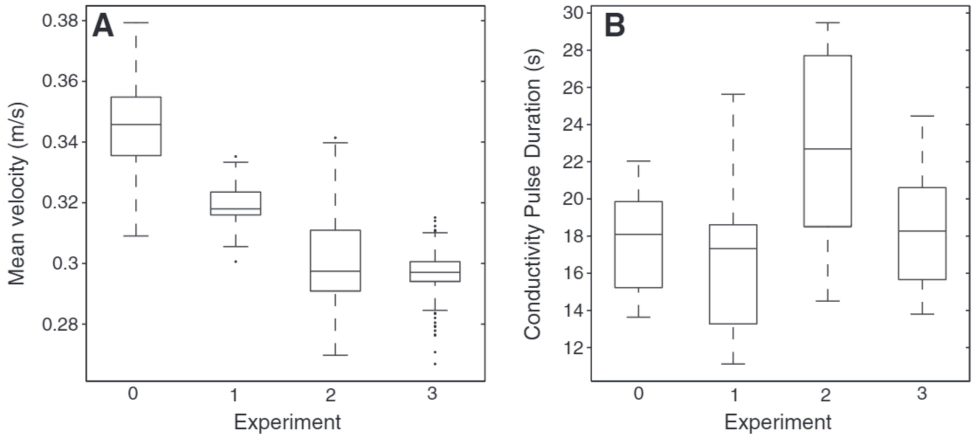

Fig. 6. (A) The distributions of mean flow velocity calculated using the peak of the conductivity pulses are shown for steady state in each experiment following treatment. (B) The distribution of conductivity pulse durations is shown.

log-affected pools were often located in straight channel segments that did not contain pools prior to wood emplacement. The percentage of pools that were log-affected varied from 33 to 70%, and appears to be positively related to the wood load and piece frequency in the reach.

The addition of large wood also affected the water surface elevation, or stage, which increased by 2.1 mm to 8.3 mm (1.4% to 5.4%) following wood addition. The increase in water surface elevation appears most strongly related to the total projected area of the pieces in the reach (Fig. 10A), but also seems to be affected by all of the other metrics except for jam frequency. The stage increase was is attributable to bed aggradation as well as increased water depth. Depth increased primarily due to decreased conveyance, but was also attributable to displacement of water by wood, which accounted for 8.5% to 17% of the total depth increase.

The increase in water stage was unevenly distributed as a result of consistently greater sediment storage in the upper segment of the reach. As a result, reach-average water surface gradient increased following wood addition and again appears most strongly related to the total projected area of the added wood (Fig. 10B). The combination of increased flow depth and water surface slope caused shear stress to progressively increase as sediment aggraded, allowing steady state sediment transport to develop. The time needed to restore steady state conditions increased with each successive experiment, and varied from 1800 to 2640 minutes, equivalent to approximately 6 to 9 years in the prototype.

4. Discussion

The experiments presented in this analysis represent a first attempt to model the reach scale morphodynamics associated with multiple pieces of large wood interacting with a mobile channel bed. Prior physical modeling studies involving mobile wood have predominantly employed a fixed bed, and have generally focused on wood transport dynamics (e.g. Braudrick et al., 1997; Braudrick and Grant, 2001; Bocchiola et al., 2006, 2008; Bocchiola, 2011). Due to the non-mobile nature of the bed in previous work, it is difficult to draw comparisons between these studies and the morphodynamic effects of wood addition observed in our experiments. Comparisons of wood transport and deposition between ours and previous studies are possible, however, and will be further examined in future research.

Previous models have also primarily used cylindrical pieces to simulate large wood (e.g. Cherry and Beschta, 1989; Braudrick et al., 1997; Braudrick and Grant, 2001; Bocchiola et al., 2006; Wilcox and Wohl, 2006; Bocchiola et al., 2008; Bocchiola, 2011). Pilot studies performed prior to our experiments, as well as previous research (e.g. Braudrick and Grant, 2000; Shields and Alonso, 2012), suggest that root wads and branches fundamentally affect wood transport processes as well as the hydraulic impact of wood pieces. In our experiments, pieces with root wads exhibited greater stability, traveling shorter distances and forming the nucleus of all of the jams that formed in the reach. These results suggest that the inclusion of some form of natural

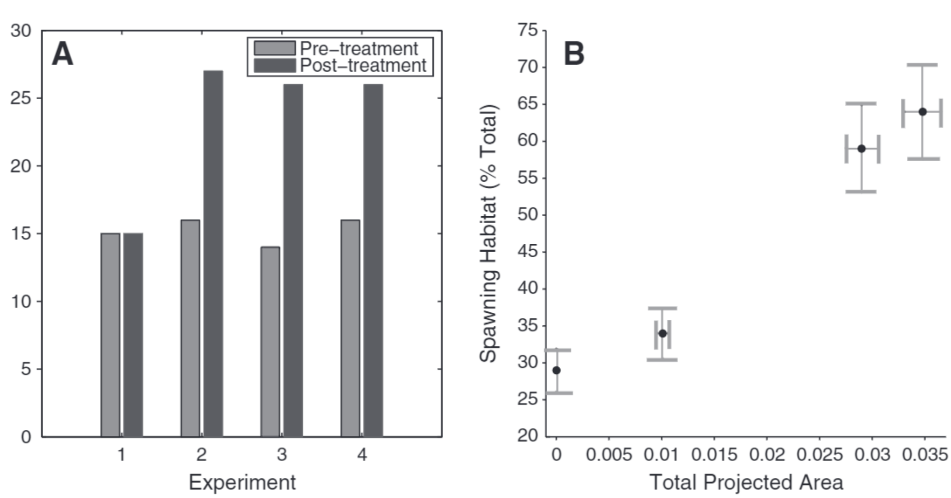

Fig. 7. (A) The number of facies prior to and following treatment are compared. (B) The percentage of the bed containing substrate suitable for spawning (D_{50}<1.0 mm) is compared with the total projected area of the wood in the reach. Error bars represent the 10% error in facies classification, as well as the 5% error in the calculation of projected areas. Note that there is no error in the projected area estimate for experiment 0, where no wood was present in the reach.

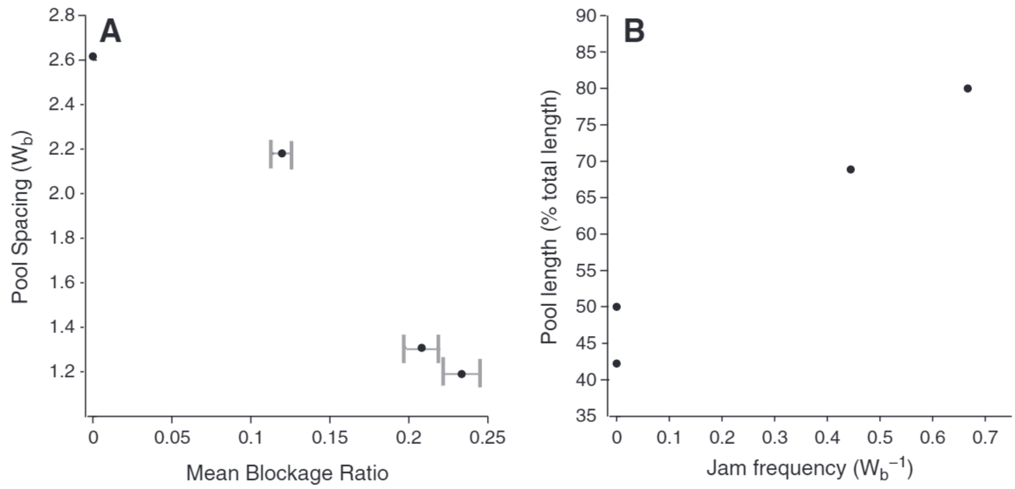

Fig. 8. (A) Pool spacing following wood addition is related linearly to the mean blockage ratio. (B) The total length of the reach occupied by pools is compared with jam frequency. Error bars (A) represent the 5% error associated with the calculation of blockage ratios. 2% error in measurements of pool length are not included in (B). Note that there is no error in the blockage ratio estimate for experiment 0, where no wood was present in the reach.

complexity in modeled wood pieces is necessary to produce realistic wood dynamics, and therefore represents a significant advance.

While prior physical models have also been used to assess the morphologic and hydraulic impacts of large wood (e.g. Cherry and Beschta, 1989; Young, 1991; Wallerstein et al., 2001; Wilcox and Wohl, 2006; Shields and Alonso, 2012), these studies largely investigate the effects of single pieces of wood on local bed morphology and hydraulics, again rendering comparisons with our work challenging. By using realistic loads of mobile wood as well as a mobile bed, our physical model better simulates natural reach dynamics where the effects of various wood pieces are superimposed. Rather than attempting to up-scale previous model data, the results generated from the reach scale model can be most usefully compared with data presented in published field studies.

The morphologic and hydraulic conditions generated by the four experiments are generally similar to field results reported in the literature. The storage efficiency of the added wood, which varied from 3.3 to 8.0 m^3 per m^3 of wood, is similar in magnitude to the average value of 3.5 m^3 of sediment storage per m^3 of wood reported by Brooks et al. (2004) following the introduction of engineered log jams in the Williams River, Australia. While the values are significantly higher than the average storage volume of 0.8 m^3 per obstruction reported by Megahan (1982) in seven Idaho streams, the results are similar when normalized by channel width.

Pool spacing prior to wood addition was similar to the range of pool spacings of 2 to 5.5 bankfull widths, and frequencies of 3–13 pools per 100 m, previously reported in streams with low wood loadings (Montgomery et al., 1995; Richmond and Fausch, 1995; Beechie and Sibley, 1997; Montgomery et al., 2003; Kreutzweiser et al., 2005), while post-addition pool spacing was similar to the spacing of <1 channel width reported by Montgomery et al. (1995) and Webb and Erskine (2003), as well as the spacing of 2–3 channel widths reported by Beechie and Sibley (1997) for reaches with moderate wood loadings. In accordance with previous studies, a large percentage of the pools were classified as log-affected at steady state following wood addition; previous authors have reported values of 48–90% for field studies (Andrus et al., 1988; Montgomery et al., 1995; Richmond and Fausch, 1995; Beechie and Sibley, 1997; Webb and Erskine, 2003). These results suggest that a large proportion of the increase in total pool length in the reach resulted from the creation of relatively small, log-affected scour pools, rather than the extension of pre-existing pools.

The number of facies increased by 63 to 86% as a result of heterogeneity in transport conditions and sediment storage, though the number of facies at steady state with wood was fairly constant regardless of the volume of wood added, as shown by Buffington and Montgomery (1999). These results suggest that the addition of relatively small volumes of wood (equivalent to 0.011 m^3/m^2 in the prototype) can produce dramatic increases in facies number, while additional wood does

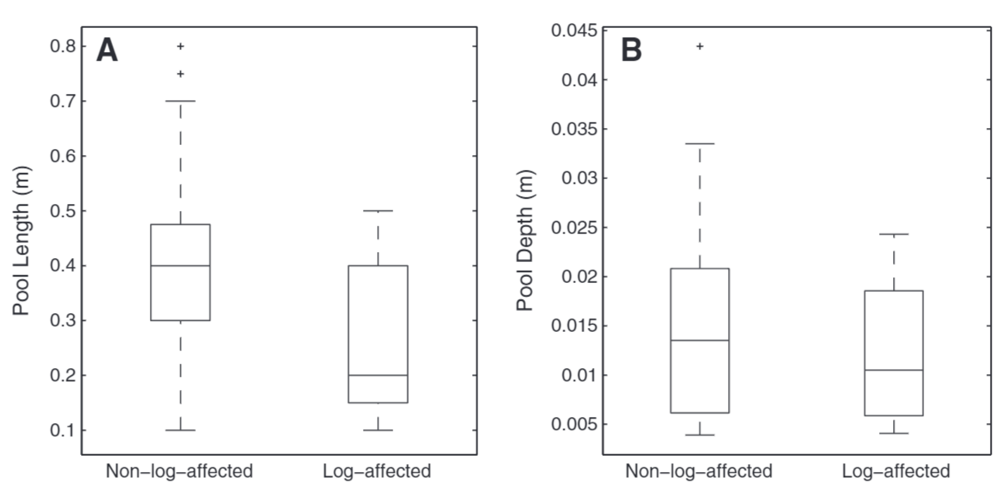

Fig. 9. (A) The distribution of pool lengths for non-log-affected and log-affected pools are compared. (B) Pool depths for each pool type are compared.

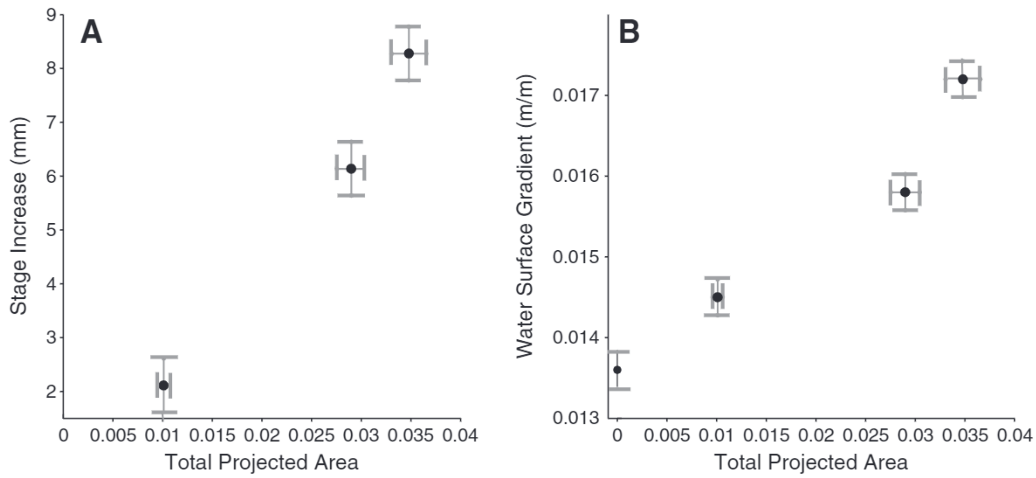

Fig. 10. Stage increase (A) and water surface gradient (B) at steady state following wood addition are compared with the total projected area of the wood in the reach. Error bars associated with the 0.05 mm measurement error are included in both figures, as well as the 5% error associated with projected area estimates. Note that there is no error in the projected area estimate for experiment 0, where no wood was present in the reach, nor is there a stage increase measurement.

not significantly alter facies complexity. Despite significant changes in facies complexity, decreases in surface grain size following wood addition were minor in experiments 2 and 3, while the increase in very coarse facies due to wood-related scour actually increased the median grain size in experiment 1. Changes in the D_{50} were small compared with decreases of 22% reported by Assani and Petit (1995) for drainage canals in France, and up to 90% decreases relative to predicted values reported by Buffington and Montgomery (1999).

Increases in water surface elevation were within the range of previously measured values: stage increases of up to 9% were measured in the Tamut River, Australia, in reaches with blockage ratios of 0.3–0.4, while debris with blockage ratios below 0.1 did not produce significant stage changes (Gippel et al., 1992, 1996). Gippel et al. (1996) also measured smaller increases of 0.8% to 1.5% in a similar flume experiment modeled on the Thompson River, Australia, while finding stage increases of only 0.2% in an undisturbed reach of the Thompson River with a median blockage ratio of 0.004. The importance of blockage ratio in producing stage increase is supported by the present research, as the dimensionless projected area of large wood appeared to be closely related to the water surface elevation increase. Wood load and piece frequency, which are both closely related to the projected area, also appeared to be linearly related to the stage increase.

Velocity decreases following wood addition were small when compared to the magnitude of the increases of 20–380% reported from field studies involving wood removal (MacDonald and Keller, 1987; Mason et al., 1990; Shields and Smith, 1992; Erskine, 1994; Reinfelds et al., 1995). This discrepancy is partially attributable to differences in measurement methods, as results from field studies are based on point measurements – often at relatively low flows – which reflect local velocities rather than true reach averages, while the model-derived measurements represent reach average velocities at high flow. The effects of large wood on flow velocity have been shown to be highly dependent on discharge (Mason et al., 1990; Shields and Smith, 1992; Wallerstein et al., 2001; Wilcox and Wohl, 2006). The discrepancy may also reflect the lower resistance provided by the modeled wood pieces, which did not contain the large branch networks often present in naturally recruited wood.

The model results also yield insight into the mechanism through which the steady state sediment transport condition is regained following wood addition. The uneven distribution of the changes in water surface elevation, which was greater at the upstream end of the reach, produced increases in reach-average water surface gradient of 0.8–29%, which were correlated to wood load as well as the projected area of the added wood. The changes in water surface gradient were large compared to the 0–10% decreases in median grain size, suggesting that morphologic rather than textural adjustment was the primary mechanism through which steady state transport conditions were restored. It appears that the combination of greater flow depth and water surface slope increased the total shear stress at steady state following wood addition, and enabled the transport capacity to recover despite sustained decreases in flow velocity, and increases in flow resistance. The adjustment of water surface gradient was closely correlated with the wood load and projected area of the wood in the reach, suggesting that the dominant channel response to wood addition may be reliably predicted for this system, and presenting a possible avenue for incorporating the effects of large wood on channel dynamics in analytical models.

The morphodynamic changes induced by the addition of large wood in these experiments have important implications for watershed management due to their potential impacts on fish habitat. Meta-analyses performed by Nagamaya and Nakamura (2010) suggest that the cover generated by pools and wood structures provides winter habitat for salmonids, thereby increasing smolt abundance in high gradient streams where refuge from high velocity flows is limiting to salmonid production (e.g. Nickelson et al., 1992; Cedarholm et al., 1997; Solazzi et al., 2000; Roni and Quinn, 2001; Johnson et al., 2005). Large wood also benefits fish assemblages by providing refuge during the dry season in lower gradient streams. The increase in pool frequency and depth variability, as well as the associated transition from plane-bed to riffle-pool morphology which occurred in all three experiments in which wood was added to the reach, therefore represents an increase in habitat quality for many fish species.

Changes in facies distribution may also benefit fish assemblages. The facies defined as very fine and fine ($D_{50}<0.7$ mm, equivalent to $D_{50}<21$ mm), which increased following wood addition in experiments 2 and 3, provide optimal spawning habitat for numerous salmonids, including pink salmon, brook trout, brown trout, and coho salmon (Buffington et al., 2004). The medium facies ($D_{50}=0.7$–1.0 mm, equivalent to $D_{50}=21$–30 mm), which increased in experiment 2, provides spawning habitat for chum salmon, steelhead, and rainbow trout (Buffington et al., 2004). The increased availability of the coarsest substrate ($D_{50}>1.4$ mm, equivalent to $D_{50}>42$ mm) in experiments 1 and 2, meanwhile, may benefit benthic species as well as other riffle-dwelling organisms (Nagamaya and Nakamura, 2010). The decrease in the availability of spawning habitat following wood addition in experiment 1, however, suggests that a threshold wood load may be necessary to retain appropriately sized spawning sediments.

Previous research has repeatedly shown that wood promotes floodplain connectivity, as water stage increases associated with large wood produce avulsions thereby creating and maintaining multi-thread channels and side-channel habitat (Collins and Montgomery, 2002; Montgomery et al., 2003; Brummer et al., 2006; Sear et al., 2010; Seo et al., 2010; Wohl, 2011; Phillips, 2012). In our experiments, an avulsion nearly occurred upstream of the largest jam in experiment 3 at Q_p; during a larger flow event the flow would almost certainly over-topped the bank, creating side-channel habitat. While floodplain connectivity is an important goal in stream rehabilitation projects and may be necessary to restore watershed processes and channel patterns, the increased risk posed by flooding must also be considered. Where pre-existing infrastructure exists, the advantages of re-establishing connectivity with the riparian ecosystem must be balanced with the desire to control flood risk (Young, 1991; Seo et al., 2010).

The favorable changes in the hydraulic and morphologic parameters are positively related to many of the wood metrics considered in the analysis. Wood load and piece frequency appear to be positively related to nearly all of the parameters considered in the analysis. Though jam frequency is generally most weakly related to morphodynamic response, it is strongly related to both pool spacing and the total pool length. This supports the assertion presented by Thompson (2012) that accumulations of interlocked logs are more effective pool forming elements than individual wood pieces. The orientation of the pieces is also important as the mean blockage ratio of the pieces is significantly related to pool spacing, and the total projected area of the pieces – a measure of both wood volume and piece orientation – appears to be the most effective explanatory variable for nearly all morphologic and hydraulic parameters. The dependence of these parameters on wood volume highlights the scale-dependence of stream rehabilitation suggested by previous authors (e.g. Sweka and Hartman, 2006; Nagamaya and Nakamura, 2010), as habitat creation is highly dependent on the volume of wood added to the reach, but the results suggest that for optimal habitat creation and predictive capacity wood orientation and jam characteristics must also be considered.

Wood removal had the opposite effects on channel processes and generally reduced aquatic habitat quality. Following wood removal, flow velocity and sediment transport rates increased, resulting in rapid evacuation of much of the stored sediment. The rates of increase in sediment transport, which varied from 3.7-fold in experiment 2 to 4.7-fold in experiment 3, were similar in magnitude to those reported from previous field studies (Beschta, 1979; MacDonald and Keller, 1987; Smith et al., 1993; Gurnell and Sweet, 1998). Despite these increases in sediment transport, however, the sediment stored following wood addition was not fully evacuated in experiment 2 or 3, suggesting that the system retained a "memory" of its previous state. As previously shown in field studies, it appears that bar preservation following wood removal may have offset the effects of resistance loss (Heede, 1972; Smith et al., 1993; Lisle, 1995).

Increased sediment transport following wood removal contributed to the in-filling of scour pools, and altered the sedimentological characteristics of the reach. Several of the log-induced pools remained following wood removal, however, sustaining the increases in pool frequency associated with large wood; while pool length decreased, pool frequency did not change. These results suggest that in-filling was insufficient to completely eliminate many log-affected scour pools. Similarly, while facies complexity decreased, the number of facies remained significantly greater than the pre-addition values. Channel gradient also remained higher compared to pre-addition values, while velocity remained lower, showing that multiple steady state energy balance configurations are possible in a single reach.

These results highlight the hysteresis in the response of the system, as wood removal produced a reach morphology and hydraulic condition which differed significantly from the original state. In accordance with results from previous research in an analogous field experiment by Brooks et al. (2006) in Australia, there was also a dramatic difference in the duration of the response; while changes in the channel morphology following wood addition occurred over a simulated period of 6 to 9 years, the morphologic adjustment following wood removal generally occurred during a single large flow event. These results have implications for future research, as many previous experiments involve the removal of large wood from stream reaches (e.g. Beschta, 1979; Heede, 1985; Smith et al., 1993; Lisle, 1995; Gurnell and Sweet, 1998), while most applications concern the addition of large wood for stream rehabilitation purposes. The differences in the channel response to wood addition and removal suggests that changes in channel morphodynamics following wood addition can not be reliably extrapolated from results generated from previous field can not be reliably extrapolated from results generated from previous experiments involving wood removal. The stark difference in response to wood addition and removal also emphasizes the importance of long term monitoring to assess the success of rehabilitation projects. Perhaps more optimistically, the success of the physical model in producing realistic reach scale responses to wood addition suggests that such models may provide a viable alternative, or at least a complement, to field studies.

5. Conclusion

Analysis of four experiments involving wood addition reveal that reach scale modeling of the complex interactions between wood and mobile sediment is possible using a scaled physical model, and can produce morphologic and hydraulic changes comparable to those observed in field studies. The results also show that wood exerts a primary control on channel morphodynamics in intermediate sized streams. The morphologic and hydraulic changes induced by the addition of large wood were shown to increase pool frequency and depth variability, enhance floodplain connectivity, and retain substrates optimal for spawning, all common objectives in stream rehabilitation programs.

Perhaps more importantly, the analysis reveals that the degree to which habitat is affected is dependent on the volume of wood added to the reach, as well as the orientation and hydraulic effectiveness of the added pieces. There is significant hysteresis in the response to the experimental treatments, as wood addition produced gradual changes in channel morphodynamics over the course of nearly a decade, while the effects of wood removal occurred during the first large flow event. Furthermore, the channel morphology at steady state was not the same following wood removal as it had been prior to addition, suggesting a morphologic memory in the system.

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